REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
4 October 2006	Final	June 2002 to June 2005

4. TITLE AND SUBTITLE
The reliability of adhesive joints under piezomechanical loading

5a. CONTRACT NUMBER
F49620-02-1-0096

5c. PROGRAM ELEMENT NUMBER
N/A

6. AUTHOR(S) S. M. Spearing (1), B. L. Wardle (1), Q Yang (2)

5d. PROJECT NUMBER
N/A

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
N/A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
(1) Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA02139, USA,
(2) Rockwell Scientific, 1049 Camino Dos Rios,
(P.O. Box 1085) Dept. 207, MS A13A Thousand
Oaks, California 91360

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research
875 N Randolph St
Arlington VA 22203
Dr Byung Lee

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Unrestricted

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

AFRL-SR-AR-TR-06-0451

13. SUPPLEMENTARY NOTES
None

14. ABSTRACT
Models were developed, validated by experiments for the cyclic loading and fatigue failure of adhesives between piezo-ceramic adherends. An analytical shear lag model and a numerically-implemented cohesive zone model were developed. The equivalence of the loading state in piezo-mechanical loading to thermomechanical actuation was established. Experiments were conducted on Lead Zirconium Titanate (PZT) substrates bonded by Lead-Tin eutectic solders. Some experiments were also conducted with a polymer adhesive. A novel test specimen, test fixture and associated power electronics were designed and fabricated. Digital image correlation was used to obtain in situ strain distributions during actuation. Damage growth and stress-life data was obtained and compared with model predictions. Once calibrated, good agreement was achieved between strain levels and fatigue life times predicted by the models and experimental data. The modeling and experimental results are significant as they provide a means to estimate the fatigue lifetime of surface-mounted piezo-actuators for active structural control as well as providing a means to conduct accelerated fatigue cycling of

15. SUBJECT TERMS
Piezoceramics, Fatigue, Adhesive Joints, Reliability, Active Materials and Structures

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unrestricted	Unrestricted	Unrestricted	None	10	Brian L. Wardle
					19b. TELEPHONE NUMBER *(include area code)* 617-252-1539

THE RELIABILITY OF ADHESIVE JOINTS UNDER PIEZOMECHANICAL LOADING

FINAL REPORT 2004

DONG-JIN SHIM[1], QINGDA YANG[2], BRIAN WARDLE[1] AND S. MARK SPEARING[1,3]

[1]Department of Aeronautics and Astronautics, MIT, Cambridge, Massachusetts
[2]Rockwell Scientific, Thousand Oaks, California
[3]School of Engineering Sciences, University of Southampton, UK

AFOSR GRANT F49620-02-1-0096

The reliability of adhesive joints was investigated using piezo-mechanical actuation. Adhesive joints are used in a wide variety of applications, and their integrity and reliability under cyclic thermo-mechanical loads are of particular importance in structural and microelectronics applications. With the increasing use of active materials such as piezo-ceramics in composite structural applications for active control, *e.g.*, [1], the integrity of the adhesive bond between the active material and structure has become a key issue. Therefore, one of the motivations of this work was to investigate the characteristics and behavior of such joints under cyclic loads. Another purpose of this work was to help characterize and understand the fatigue behavior of solder joints used in microelectronics where thermomechanical stresses are a key concern.

The AFOSR-sponsored work focused on characterizing the behavior of various types of solder joints using piezo-mechanical actuation. Solder joints play a very important role in microelectronics packaging, providing electrical and mechanical connections between different components, and thus, their reliability is a key concern. It is well-known that the main failure mechanism of solder joints is thermally-induced fatigue, *e.g.*, [2]. However, solder joints generally undergo both time-dependent and temperature-dependent processes under thermo-mechanical loads that complicate their behavior, making accurate life predictions very difficult, *e.g.*, [3]. The reliability of solder joints is generally demonstrated via extensive testing. Commonly used accelerated testing methods are thermal cycling and mechanical cycling , *e.g.*, [4]. However, for thermal cycling, in order to achieve thermal equilibrium in each cycle, testing must be performed at slow rates with sufficient hold times, and for mechanical testing, the applied stress and strain states do not exactly replicate the thermo-mechanical loads in actual solder joints. Piezo-mechanical actuation is an attractive alternative method for accelerated testing because the deformation of piezo-ceramic materials under an electric field is similar to thermally-induced deformation of conventional materials and testing can be performed at a faster rate. The feasibility of piezo-mechanical actuation for solder joint characterization was demonstrated in a previous investigation where cracks in the solder layers were induced in bonded piezo-ceramic joints [5]. The current work sought to build on this previous work and provide a robust methodology for accelerated testing of solder joints using piezomechanical actuation and a better understanding of the temperature and time-dependent effects that exist in many solder joint applications.

EXPERIMENTAL APPROACH

The active piezo-mechanical joint consists of a three layer, double lap joint piezo-stack using lead-zirconate-titanate (PZT) 5H and solder alloy, as shown in Figure 1. By applying an appropriate combination of DC and AC voltages at the top and bottom surfaces of each piezo layer, the layers can be actuated such that the two outer layers deform out-of-phase relative to the middle layer. This causes shear stresses/strains in the solder joints. An illustration of the actuation scheme is shown in Figure 2. The double-lap geometry and actuation scheme allows stress and strain levels similar to those that would be achieved in conventional thermal cycling of joint between two adherends with different thermal expansion coefficients, in addition to eliminating bending of the piezo-stack.

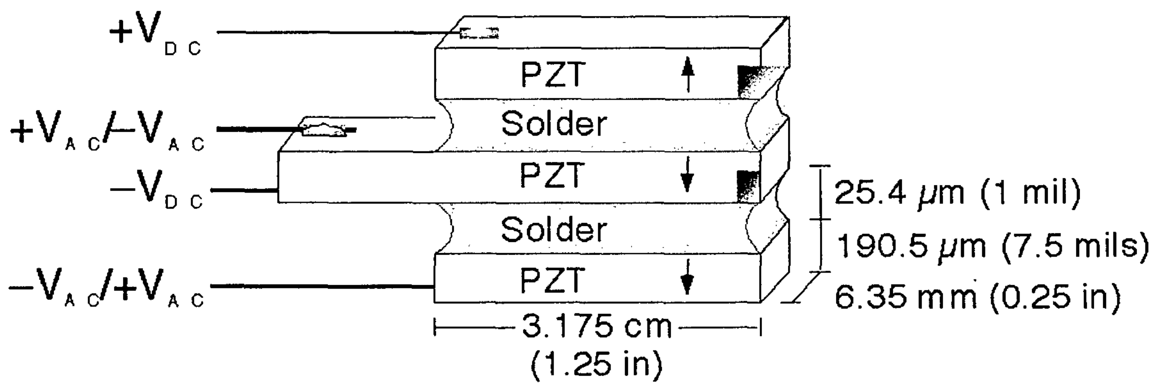


Figure 1. Schematic of specimen design and relative potentials of layers.

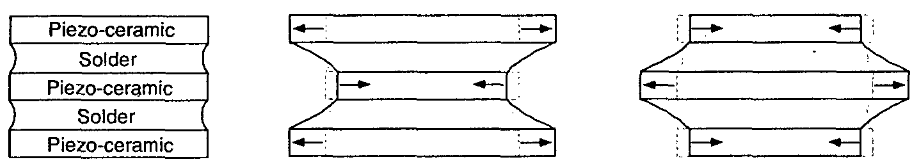


Figure 2. Schematic of actuation scheme.

From preliminary experimental work, it was found that actuation levels attainable via piezoelectricity in the current active piezo-mechanical joint are relatively low compared to mechanical and thermal cycling. This is principally due to dielectric breakdown, due to surface conduction paths, and the presence of moisture in the air. To improve this situation a new specimen holder was developed, which could be immersed in silicone oil. This improved the breakdown characteristics considerably, and has allowed electric field strengths to be achieved which are nearly double those achieved in the earlier studies [5]. The oil is sufficiently transparent that damage evolution can be monitored *in situ*. Also, immersion in oil has the advantage of improving the heat transfer characteristics so that more accurate temperature control can be achieved. A picture of the test fixture is shown in figure 3.

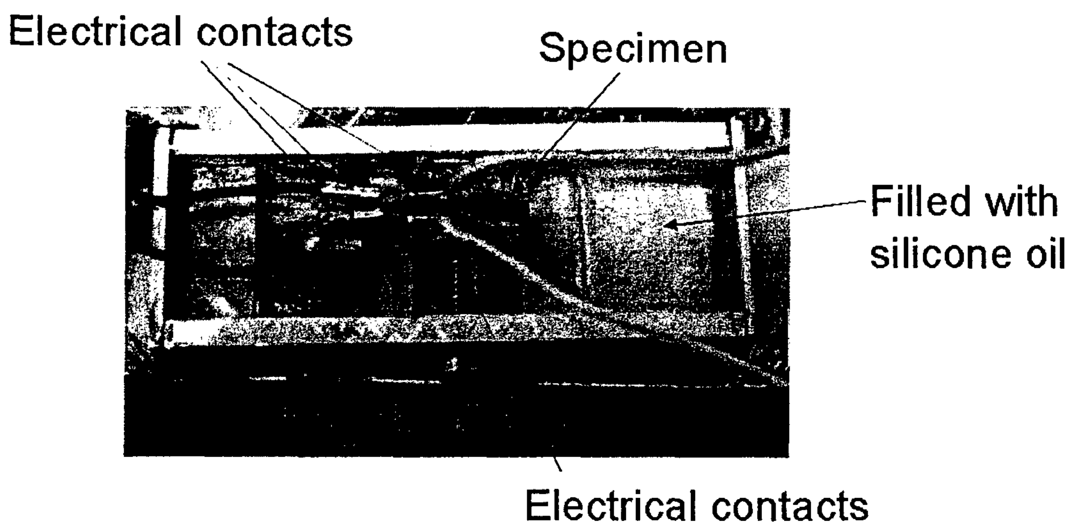


Figure 3. Improved specimen holder in which specimen is immersed in silicone oil to prevent dielectric breakdown

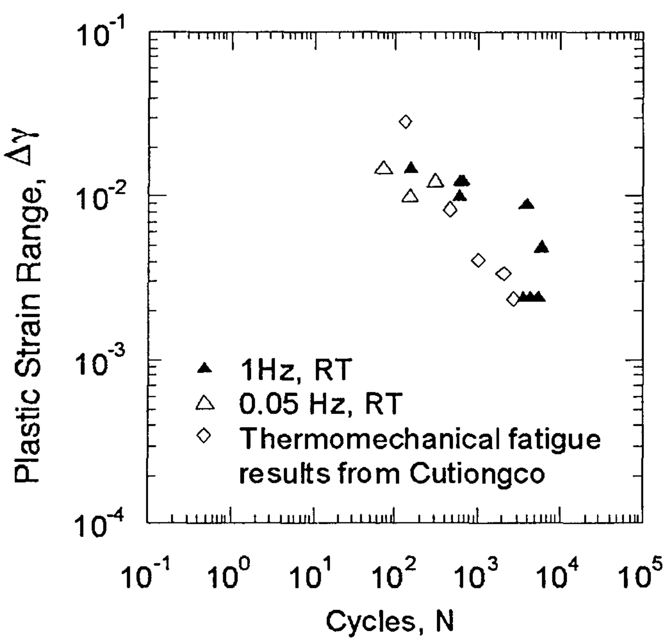


Figure 4. S-N data for piezo-actuated fatigue at two frequencies, compared with thermomechanical fatigue results from the literature.

EXPERIMENTAL RESULTS

Using this improved fixture new data was obtained for the fatigue behavior of eutectic Sn-Pb using the active piezo-mechanical joint under various test conditions. Data was obtained in the form of S-N curves (figure 4). Observations of crack initiation and growth were consistent with those of previous work and were also very similar to results obtained from thermal cycling of solders between substrates with a thermal expansion mismatch [4]. Significant diffusion of the gold used to promote wetting and adhesion of

the solder to the piezo-substrates were observed, coupled with grain growth (figure 5). Fatigue cracks tended to initiate at voids and then propagated stably over several millimeters of the joints (figures 6). In many cases fracture initiated at voids or free edges in a cohesive mode and then propagated adhesively at the interface between the solder and the metallized piezo-ceramic as shown in figure 7. In some cases fracture of the piezoceramics occurred, presumably due to the evolution of bending stresses due to asymmetric crack growth.

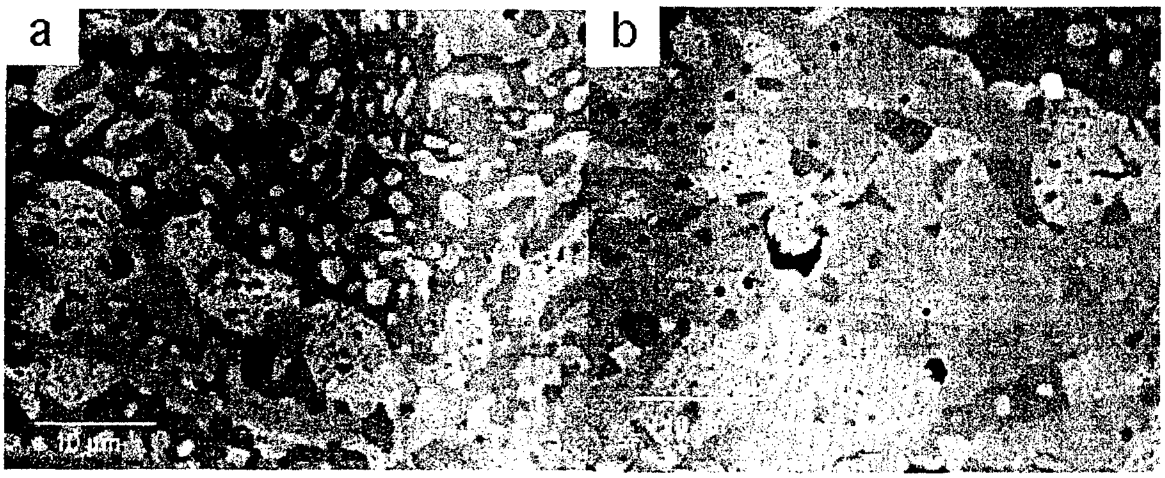


Figure 5. Micrographs showing grain growth and evidence of gold diffusion between a solder joint (a) before cycling and (b) after 4,000 fatigue cycles.

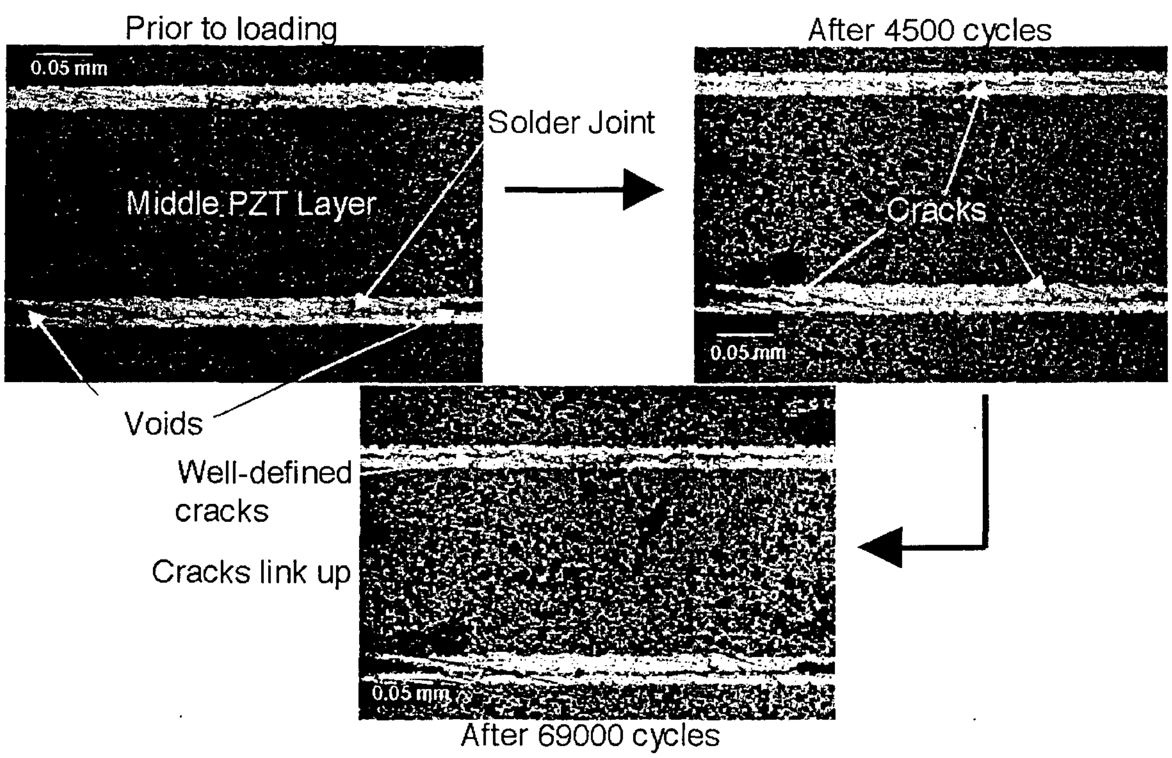


Figure 6. Micrographs showing the initation of fatigue cracks at voids and their subsequent stable growth.

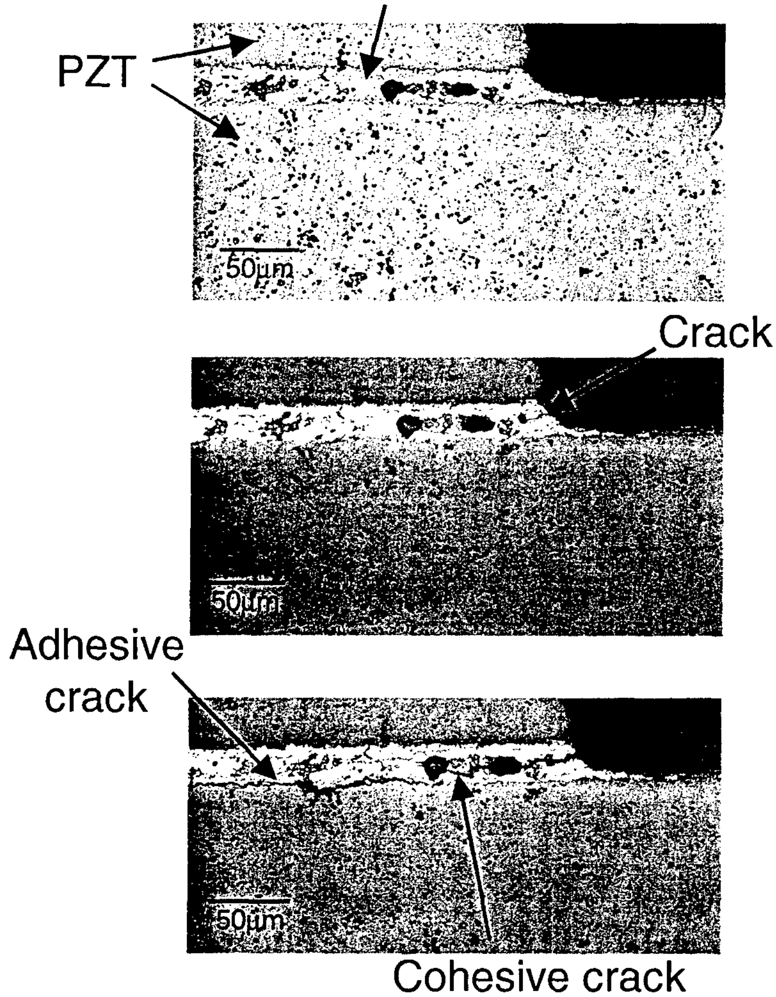
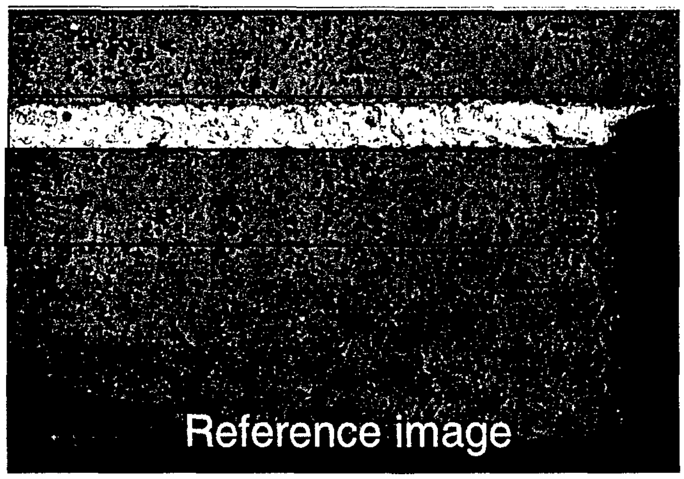


Figure 7. Micrographs showing the initiation of fatigue cracks at voids and their subsequent stable growth.

MODELING

A shear lag model was developed which modeled the piezo-ceramic layers as piezo-elastic and the solder as a perfectly plastic material capable of transmitting shear at its yield stress τ_y. This model was compared to experimental results obtained by digital image correlation. A commercial system was employed to obtain *in situ* displacement and hence strain fields of the deformed and undeformed piezo-fatigue specimens. Figure 8 shows the regions mapped and the resulting displacement distribution. This information was then used to compare with the shear lag model. A finite element model was also developed for further comparison. Strain distributions between the two models and the experimental data are compared in figure 10. Reasonable agreement is obtained between both models and the experimental data near the free edge of the specimen. Further away from the free edge the agreement is less good. The finite element model

and shear lag model predict similar trends. Further analysis of the boundary conditions imposed by the specimen holder suggested that these play a role in defining the strain distributions observed in experiments. A revised finite element model (Figure 10) was constructed which included the constraining effect of the electrical contacts. This model generated strain distributions along the line of the solder joint as shown in figure 11 which were closer to those observed in the experiments, suggesting that the constraint imposed by the electrical contacts is indeed significant.



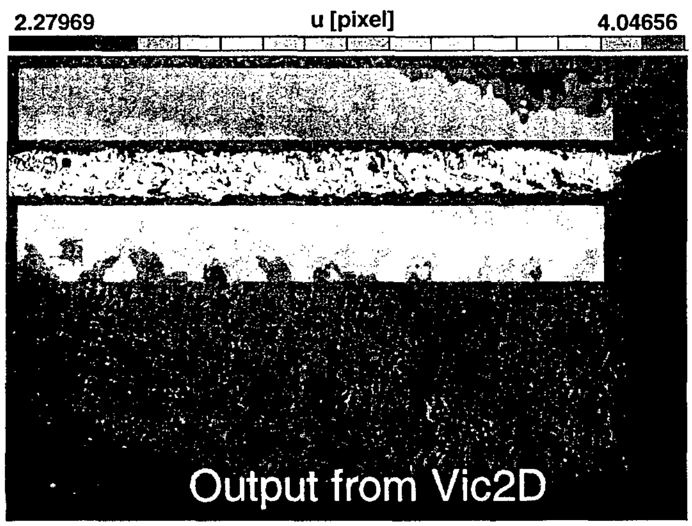


Figure 8. (a) Reference image for digital image correlation and (b) resulting displacement map of a deformed specimen.

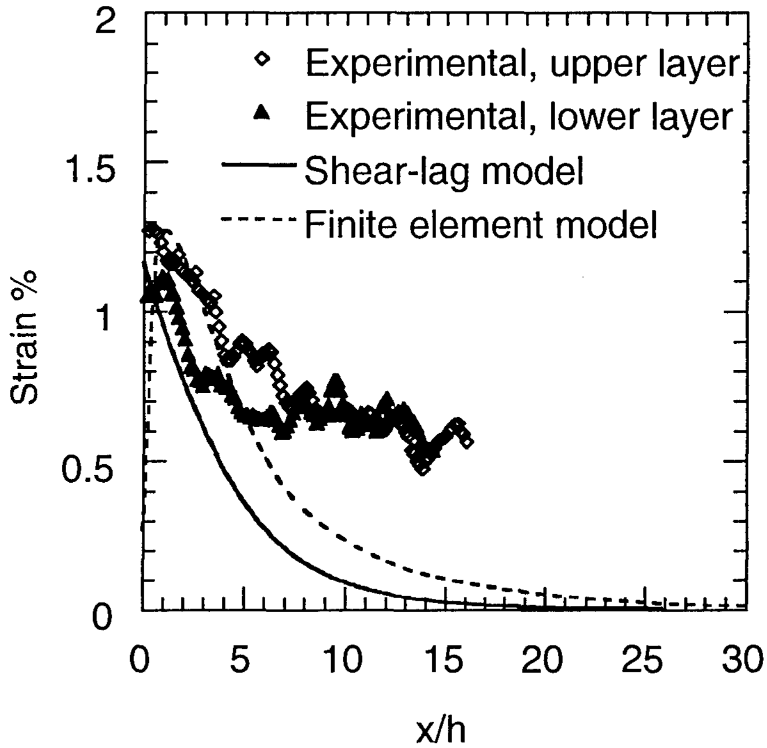


Figure 9. Comparison of strain distributions predicted by the shear lag model, finite element model and experimental data obtained by digital image correlation.

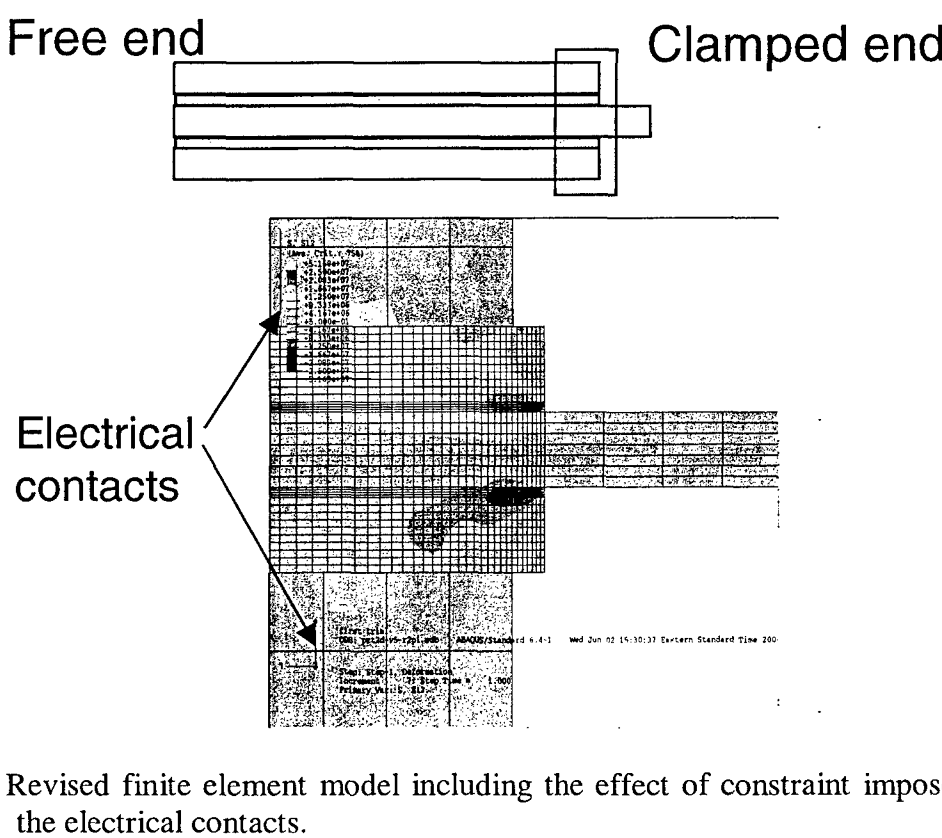


Figure 10. Revised finite element model including the effect of constraint imposed by the electrical contacts.

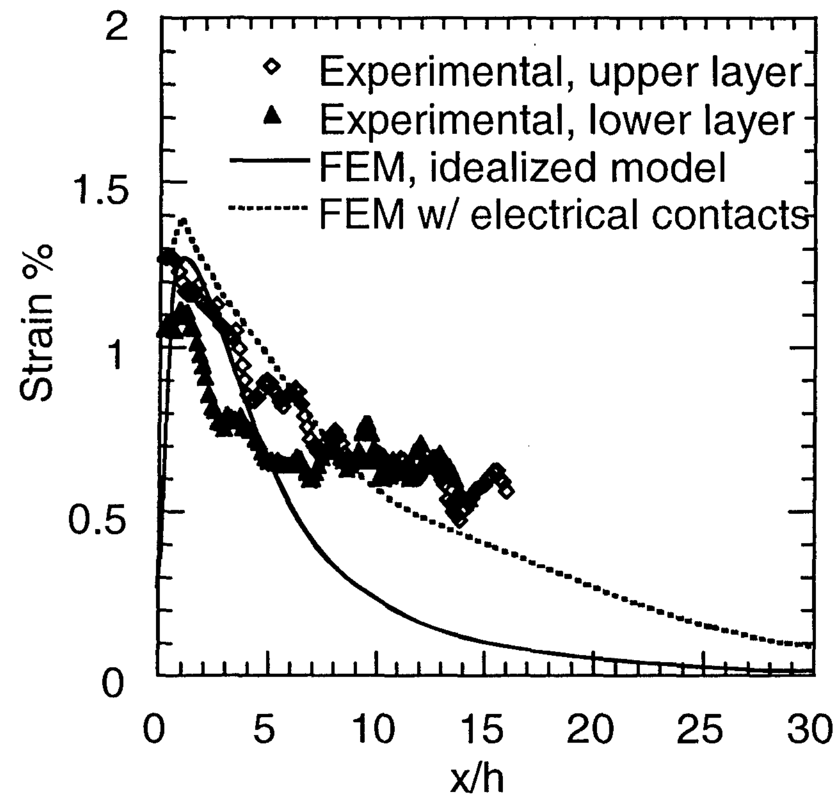


Figure 11. Comparison of the revised finite element model, including the effect of constraint imposed by the electrical contacts and experimental data.

Two approaches to life prediction were via the use of analytical and finite element models. The analytical model provides a simple and efficient means to verify and validate experimental measurements, while the finite element method provides a more accurate analysis. The analytical model consists of the shear lag model utilizing a constant shear stress for the solder. This can then be used to evaluate the plastic strain range and life prediction achieved using a conventional or modified Coffin-Manson model. The finite element model has an embedded cohesive damage zone model to describe the crack growth in the solder via traction-separation laws, *e.g.*, [6,7]. The traction-separation law has been calibrated using literature data from thermal cycling tests. The calibrated cohesive zone model has been applied to the piezo-mechanical data of figure 4, and a good agreement obtained, as shown in figure 12. A journal paper on the cohesive zone modeling effort has been published [8]. A journal paper providing an overall summary of the experimental and modeling work has been accepted for publication [9]

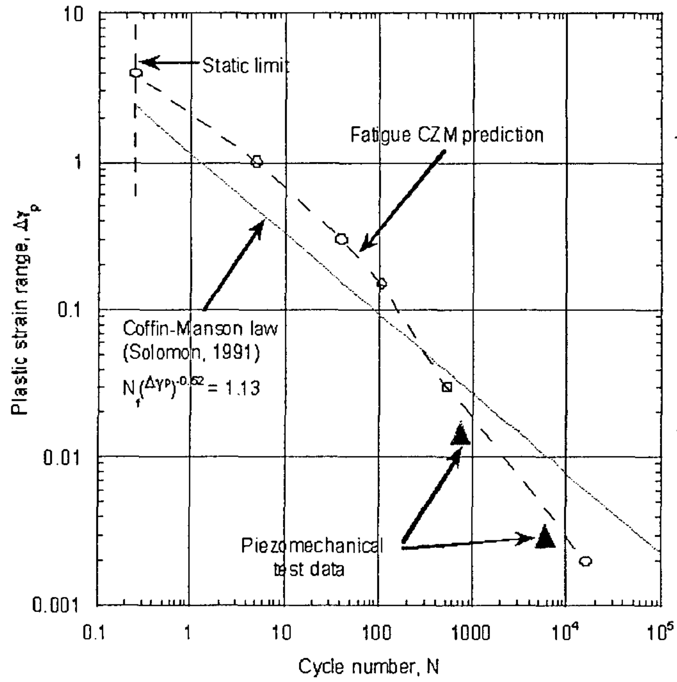


Figure 12. S-N data for thermal fatigue and piezo-fatigue of Pb-Sn eutectic solders with the Cohesive Zone Model superimposed.

The utility of this work for microelectronics applications is that it provides the basis for use of piezomechanical actuation for accelerated testing to assess the durability and reliability of solder joints, in addition to providing new insights into their fatigue characteristics. This is particularly useful and relevant at the present time given the increasing trend of using lead-free solders due to environmental concerns in lead-based solders. An efficient and reliable accelerated testing method based on piezo-mechanical actuation would be of great benefit in characterizing new types of solder alloys. Overall, the use of piezo-mechanical actuation for durability and reliability of adhesive joints has great potential for use in a wide range of problems in aerospace structures, microelectronics and microelectromechanical systems (MEMS) packaging where thermo-mechanical fatigue is an issue. The work conducted in this project has established the foundations for the utilization of piezo-mechanical actuation for generic adhesive materials.

PROJECT ACHIEVEMENTS

1. Established the use of piezo-generated fatigue loading as an analogue for thermomechanical fatigue loading of adhesive joints. Equivalence established via comparison of S-N data and equivalence of local strain distributions.
2. Development of life-prediction modeling techniques, including the effects of damage accumulation as a function of cycling and temperature. These will have utility in conjunction with accelerated test methods.

3. Integration of a suite of experimental techniques that will allow accelerated testing of solders and other adhesives for which thermomechanical durability is an issue.
4. Identification of the importance of local boundary conditions and defects in determining the lifetime of solder joints. This implies that detailed design can have a significant effect on component life as well as process control.
5. Two journal papers have been published directly stemming from this work.
6. Dr. Dong Jin Shim, the post doctoral researcher working on the project has been hired to a permanent position by the General Electric Corporation and now works at their research center in Schnectady.

References

[1] Friedmann, P. P., "The Promise of Adaptive Materials for Alleviating Aeroelastic Problems and Some Concerns, " Proceedings of Innovation in Rotorcraft Technology, Royal Aeronautical Society, London, United Kingdom, June 24-25, 1997.

[2] Lau, J.H., Ed., "Solder Joint Reliability", New York, NY: Van Nostrand Reinhold, 1991.

[3] Solomon, H.D. "Predicting thermal and mechanical fatigue lives of soldered joints from isothermal low cycle data. " In Book: Solder Joint Reliability. Ed: J.H.Lau. New York, NY: Van Nostrand Reinhold, 1991.

[4] Gau, Q., E.C. Cutiongco, L.M. Keer, M.E. Fine, "Thermomechanical Fatigue Life Prediction of 63Sn/37Pb Solder", Journal of Electronic Packaging, 114, 1992, pp. 145-151.

[5] Sanders, C.L., "Piezo-Induced Fatigue of Solder Joints," S.M. Thesis, MIT, 2000.

[6] Tvergaard, V., and Hutchinson, J.W., "The Relation Between Crack Growth Resistance and Fracture Process Parameters in Elastic-Plastic Solids," Journal of the Mechanics of Physics of Solids, 40, 1992, pp. 1377-1397.

[7] Yang, Q.D., Thouless, M.D., and Ward, S.M., "Numerical Simulations of Adhesively-Bonded Beams Failing with Extensive Plastic Deformation," Journal of the Mechanics of Physics of Solids, 47, 1999, pp. 1337-1353.

[8] Q. Yang, D-J. Shim, and S. M. Spearing, "A Cohesive Zone Model for Low Cycle Fatigue Life Prediction of Solder Joints" Microelectronic Engineering, **75**(1), 85-95, 2004

[9] D-J. Shim, S. M. Spearing, Q. Yang *"Crack initiation and growth in solder joints under cyclic shear deformation using piezomechanical actuation"*, Accepted for publication, J. Engineering Materials and Technology, August 2005